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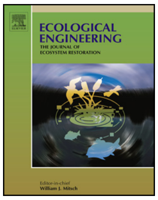

Sedimentation and resuspension modelling in free water surface constructed wetlands

S. Gargallo*, M. Martín, N. Oliver, C. Hernández-Crespo

Research Institute of Water and Environmental Engineering (IIAMA), Universitat Politècnica de València, Cno. de Vera s/n, Valencia, Spain

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ABSTRACT

Eutrophication is a widespread problem that is being tackled from many perspectives and the recently applied technology of constructed wetlands is being used in the treatment of eutrophic water. However, process-based models to simulate their performance are scarce, so in this work a mechanistic model was developed to simulate the removal of total suspended solids, phytoplankton and total phosphorus in free water surface constructed wetlands treating eutrophic water. The model represents the influence of the main factors of the biotope and biota on these water quality variables, and particular attention is paid to resuspension produced by wind and by avifauna. Likewise, the effect of emergent vegetation cover in sedimentation, resuspension and phytoplankton growth is included. Phytoplankton is considered to store phosphorus internally in order to use it when growing, and the contribution of phytoplankton concentration to the suspended solids budget is included. The software AQUASIM was used to calibrate and validate the model in two full-scale constructed wetlands treating eutrophic water from Lake l'Albufera de València (Spain) for three years. The simulated data and field measurements showed satisfactory adjustments for the three studied variables. The budgets obtained for each variable reveal that sedimentation and resuspension are the main processes in total suspended solids performance. Sedimentation of organic particulate phosphorus is the most important process in total phosphorus removal. The sum of the effect of resuspension by avifauna and by wind increases by more than 50% the quantity of solids that enters the water column. The model reveals that simulating the effects of the emergent vegetation cover and resuspension is crucial for representing the performance of the studied variables.

1. Introduction

Loss of water quality in natural water bodies has become a major environmental problem for decades and many initiatives aimed at recovering good environmental status have been carried out. Eutrophication is one of the most globally widespread problems and it is considered one of the main stressors on lakes (Ballatore and Muhandiki, 2002). In eutrophic water bodies, turbidity is a critical parameter that needs to be controlled in order to recover submerged aquatic vegetation and biodiversity (Scheffer et al., 1993).

This issue has been approached from a wide range of perspectives, such as the termination of untreated sewage discharges or the improvement in wastewater treatment techniques. In other cases, eutrophic waters have been treated by using different engineered bioremediation technologies, including constructed wetlands (CWs) (Coveney et al., 2002; Wu et al., 2010).

The modelling of CW performance was initiated with the development of first-order decay models (Kadlec and Knight, 1996; Stone et al., 2004), which were based on input/output data and the treatment processes were considered as a figurative black box. These models were simplifications of the complex wetland processes and more knowledge was needed in order to optimize the performance of CWs. Accordingly, multiple experiments and research have been carried out and a greater level of understanding has been achieved, partly due to the development of mechanistic or process-based models (Min et al., 2011). Mechanistic models use mathematical formulation to represent the processes that affect each variable inside a CW and are useful to clarify which are the key processes and how they work in CW performance.

An intermediate model between these two types is the autobiotic model developed by Kadlec (1997), which provides a low-level mechanistic explanation of phosphorus removal processes in CWs by using a first order biomass-based rate.

Over the last two decades, a great leap forward in mechanistic models for CWs has taken place (Meyer et al., 2015). Most of them were applied to simulate urban wastewater treatment in

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* Corresponding author.
E-mail address: sagarbel@upv.es (S. Gargallo).

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subsurface flow CWs (SSFCWs), e.g. Constructed Wetlands 2D (CW2D) (Langergraber, 2001) and Constructed Wetland Model number 1 (CWM1) (Langergraber et al., 2009), which are based on the mathematical formulation of the Activated Sludge Model series (ASMs) (Henze et al., 2000). Mburu et al. (2012) implemented CWM1 in AQUASIM and one of the most widely used application of models CW2D and CWM1 is the Wetland Module in HYDRUS software (Langergraber and Šimůnek, 2012). The model FITOVERT (Giraldi et al., 2010) also uses a biochemical module based on ASMs for simulating organic matter and nitrogen in SSFCWs. Likewise, a high level of detail is achieved, e.g. BIO_PORE model (Samsó and García, 2013) is able to simulate biofilm growth and clogging in porous media.

On the other hand, RWQM1 (Reichert et al., 2001) is a mechanistic model also based on the structure of ASMs models where microalgae performance is simulated in rivers.

Nevertheless, mechanistic models developed for free water surface constructed wetlands (FWSCWs) are less numerous, and those models developed for SSFCWs or river water quality cannot be directly used in these systems. Mulling (2013) deeply studied suspended particles removal in FWSCWs and determined the changes in the type and nature of these particles throughout the treatment. Besides physical, chemical and biological processes, FWSCWs maximize the interactions with the environment and the biota. In particular, some of the most influential factors in FWSCWs are related to wind action and bioturbation (Onandia et al., 2015), which are not included in the abovementioned models.

Although some mechanistic models were developed for FWSCWs, interactions with biotope and biota are not strongly studied. A remarkable advance is the modelling developed in the stormwater treatment areas of Everglades National Park where particular attention was paid to phosphorus removal (Wang and Mitsch, 2000; Min et al., 2011). Other models were developed to simulate nitrogen, phosphorus and suspended solids from nonpoint source pollution (Chavan and Dennett, 2008) or from urban wastewater (Wang et al., 2012).

In order to optimize eutrophic water treatment and total suspended solids (TSS) removal in FWSCWs, it is necessary to have available an appropriate mechanistic model where the main components involved are simulated.

This study aims to develop a mechanistic model for FWSCWs treating eutrophic water in order to simulate the removal of TSS and its relation to phytoplankton and total phosphorus. This work is focused on TSS because increasing water transparency is an essential factor in achieving good ecological status in water bodies. The model will facilitate an overview of the CWís performance within its environment since interactions with biota and biotope are included. For this reason, the model is calibrated and validated in two full-scale FWSCWs treating hypertrophic water (named FG1 and FG2). These FWSCWs are located in *Tancat de la Pipa,* a protected area near the eutrophic shallow Lake líAlbufera de València (Spain), where the high concentration of total phosphorus (TP) and TSS hinder the recovery of the good environmental status of the water body.

This model will increase the understanding about the different processes that affect suspended solids, phytoplankton and total phosphorus by bringing to light how they work and to what extent they affect concentrations. In addition, the model could be used as a management and design tool to improve FWSCWís performance.

2. Methods

In this section a full appraisal of the mechanistic model is presented. Furthermore, the study site where the calibration and validation were carried out is described and the sensitivity analysis is set forth in detail.

Table 1
Description of the components included in the model.

Component	Description	Unit
TIP	Total inorganic phosphorus.	$\mathrm{mg\,P\,L^{-1}}$
OP	Organic phosphorus.	$\mathrm{mg\,P\,L^{-1}}$
P_{int}	Phosphorus accumulated inside the phytoplankton cells.	$\mathrm{mg\,P\,mg\,Chl}\,a^{-1}$
X_P	Phytoplankton biomass.	$\mathrm{mg\,Chl}\,a\,\mathrm{L^{-1}}$
X_{TSS}	Total suspended solids.	$\mathrm{mg\,dw\,L^{-1}}$

2.1. Model description

The proposed model is implemented in the software AQUASIM (Reichert, 1998). The model structure is based on processes reactions which are included in the software as dynamic processes. Components of the model are introduced as state variables and the rest of parameters are introduced as programme, constant, real list or formula variables. The mixed reactor compartment configuration is used and defined by the volume of the wetland, active variables, active processes, initial conditions and inputs. The variable-order Gear integration technique is used to solve the differential equations (Reichert, 1998).

The model describes the processes, kinetics and stoichiometric coefficients that determine the performance of each component. The mass balance for each component is calculated by Eq. (1):

$$\frac{d\,VC_n}{dt} = Q_{in}C_{in,n} - Q_{out}C_n + Q_{rf}C_{rf,n} - Q_{et}C_{et,n} \pm Q_{gr}C_{gr,n} + Vr_nC_n \tag{1}$$

where n = 1,2. . .m, *m* is the total number of components, V (L) is the water volume, t (s) is time, C_n ($\mathrm{mg\,L^{-1}}$) is the outlet concentration of the component *n*, Q_{in} ($\mathrm{L\,s^{-1}}$) is the inlet flow, $C_{in,n}$ ($\mathrm{mg\,L^{-1}}$) is the inlet concentration of the component *n*, Q_{out} ($\mathrm{L\,s^{-1}}$) is the outlet flow, Q_{rf} ($\mathrm{L\,s^{-1}}$) is the direct rainfall flow entering to the system, $C_{rf,n}$ ($\mathrm{mg\,L^{-1}}$) is the concentration in the rainfall of the component *n*, Q_{et} ($\mathrm{L\,s^{-1}}$) is the flow that leaves the system due to evapotranspiration, $C_{et,n}$ ($\mathrm{mg\,L^{-1}}$) is the concentration in the evapotranspiration of the component *n*, Q_{gr} ($\mathrm{L\,s^{-1}}$) is accounting for the gains or losses of the system by percolation to groundwater, $C_{gr,n}$ ($\mathrm{mg\,L^{-1}}$) is the concentration in the percolation flow of the component *n* and r_n ($\mathrm{d^{-1}}$) is the reaction rate for the component *n*. Concentration of the component *n* in the evapotranspiration flow is assumed to be equal to zero. r_n is calculated as shown in Eq. (2):

$$r_n = \sum_{j=1}^{R} \upsilon_{n,j} r_j \tag{2}$$

where *j* = 1,2...R, R is the total number of processes, $\upsilon_{n,j}$ is the stoichiometric factor for component *n* and process *j*, and r_j ($\mathrm{d^{-1}}$) is the reaction rate for process *j*.

Components included in the model are shown in Table 1. Phytoplankton was included in order to study the contribution of its dry weight to the TSS budget and due to its relevance in the eutrophication process, and phosphorus was introduced because its particulate forms are linked to the performance of TSS and it is usually the limiting nutrient in eutrophic water.

The component X_P represents the entire phytoplankton biomass and TP was calculated as shown in Eq. (3), where i_{PXp} ($\mathrm{mg\,P\,mg\,Chl}$ a^{-1}) is the content of phosphorus in phytoplankton tissues:

$$TP = TIP + OP + P_{int} \cdot X_P + X_P \cdot i_{PXp} \tag{3}$$

Phosphorus is divided into organic and inorganic forms. OP concerns both particulate and dissolved forms and is subjected to the